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TTCS Heat eXchanger Bread Board Model Test Report

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Summary

For the AMS experiment onboard the International Space Station a thermal control system, known as the Tracker Thermal Control System (TTCS) is being developed. The TTCS basically consists of a mechanically pumped two-phase loop, where heat is collected at two evaporators and rejected at two radiators. The loop contains carbon dioxide (CO_2).

One of the components of this loop is the Heat eXchanger, used to heat up the CO_2 liquid entering the evaporators.

This document describes the tests performed on the Bread Board Model Heat eXchanger to determine its Overall Heat Transfer Coefficient.

The HX was also successfully tested in a representative CO_2 laboratory test rig where typical orbital parameters were applied. The results were very promising.

Document Change Log

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1 Introduction

The main objective of the Tracker Thermal Control System (TTCS) is to provide accurate temperature control of the AMS Tracker front-end electronics (known as ‘the hybrids’). Therefore the evaporators have to operate at a uniform temperature and the CO_2 fluid has to enter the evaporators close to, or at saturation temperature. Pre-heaters are defined to heat up possible sub-cooled CO_2 liquid leaving the condensers and entering the evaporators. The use of a Heat eXchanger, which exchanges heat between in and outlet of the evaporators, can relief the task of the pre-heaters and has the following advantages:

- Less electrical power is required for the pre-heaters
- Because of lower additional pre-heater power, the condenser radiators can be designed smaller, or operation is possible at lower temperatures
- It will lower the risk of malfunction as the Heat eXchanger is a passive device which will always help to increase the evaporator inlet temperature
- As part of the evaporator outlet vapour will partly condensate in the HX, lower CO_2 quality will flow through the condenser feed lines which in turn will lower the overall system pressure drop

Important parameters for a plate heat exchanger that affects the overall heat transfer coefficient are the effective heat transfer area and the allowed pressure drop. Minimising the overall system pressure drop is a main driver throughout the TTCS project. As increasing the OHTC-value comes at the expense of increasing pressure drop –which in this project is to be minimised- the HX will not be as compact and/or as effective as otherwise possible.

The OHTC is a difficult parameter to calculate analytically and in literature on the subject, it is found that for practical use one generally measures thermal parameters for a specific plate geometry and is then able to calculate the performance when the number of plates and or size is varied.

2 Objective

The objective of the tests is to determine the Overall Heat Transfer Coefficient of the Bread Board Model Heat eXchanger.

3 Hardware under test

The hardware under test consists of the Bread Board Model Heat eXchanger as depicted in *Figure 3-1* and *Figure 3-2*.

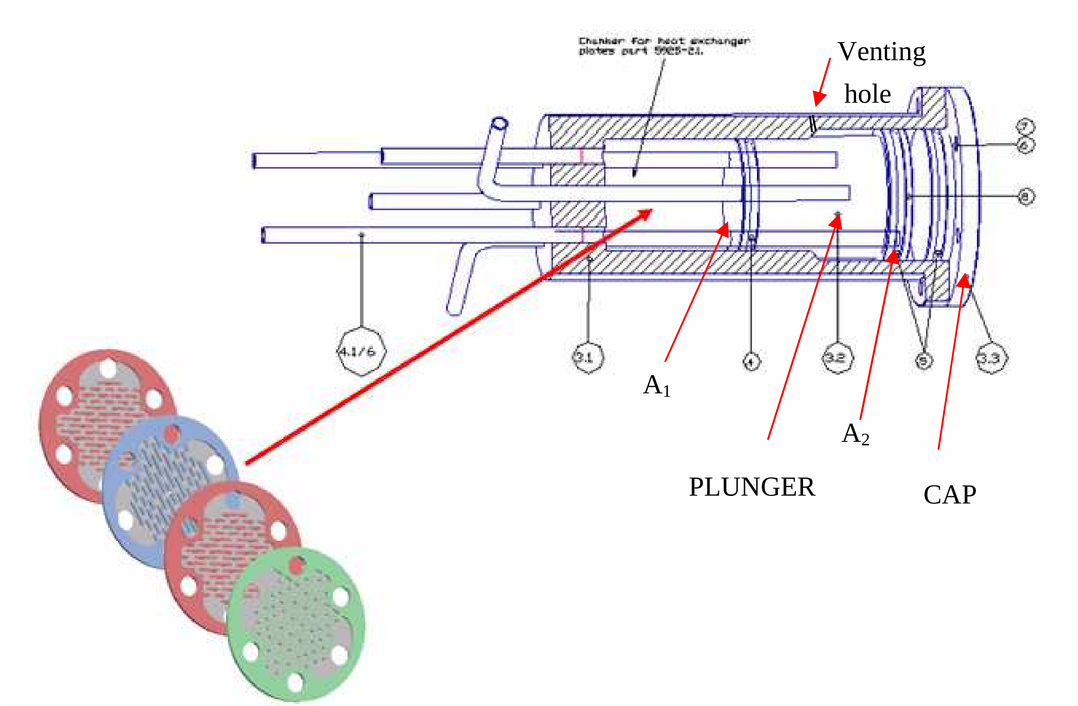

Figure 3-1: Bread Board Model Heat eXchanger 3-D view,
here drawn with 4 plates outside the housing

The plate type Heat eXchanger comprises a cylindrical shaped stainless steel housing containing a maximum of 36 aluminium plates. The Bread Board Model is designed such that the number of plates can be varied relatively easy by removing the cap and plunger, adding or removing plates, and mounting plunger and cap again. Adding plates will decrease the pressure drop across the HX while it will increase the effective heat exchanging area. The HX mainly consists of three channels (2 liquid and 1 two-phase) that all can exchange heat. At the time of the HX construction the stage of the project demanded 2 liquid inlets; further details on the reason why are out of the scope of this report. The plates are stacked in the following order: X, L1, X, L2 where X= two-phase, L1 and L2=liquid. 18 plates are used for two-phase and 18 plates for the liquid phase and they are stacked and firmly pressed on top of each other by a plunger. The plunger is sealed by two O-rings and constructed with two different area's, A_1 and A_2 causing the plunger to move -in this case to the left- by a force $F=p*(A_2-A_1)$, where p is the system pressure. The volume between the plunger front and rear O-rings is vented to the environment by a small venting hole.

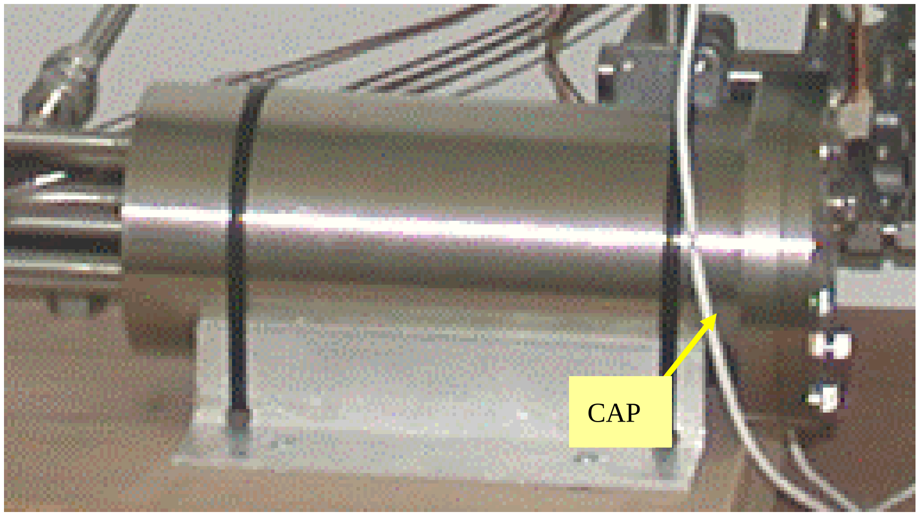

Figure 3-2: Picture of the Bread Board Heat eXchanger mounted in the test rig

Figure 3-3 shows a picture of one -out of 36 identical- aluminium plates used in the Bread Board Model HX.

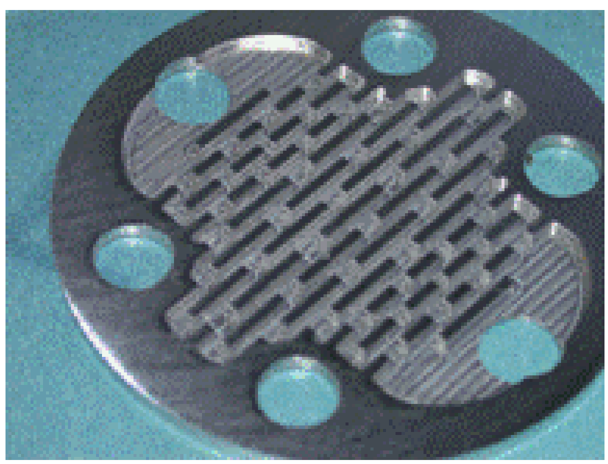

Figure 3-3: Picture of one out of 36 Bread Board Heat eXchanger plates

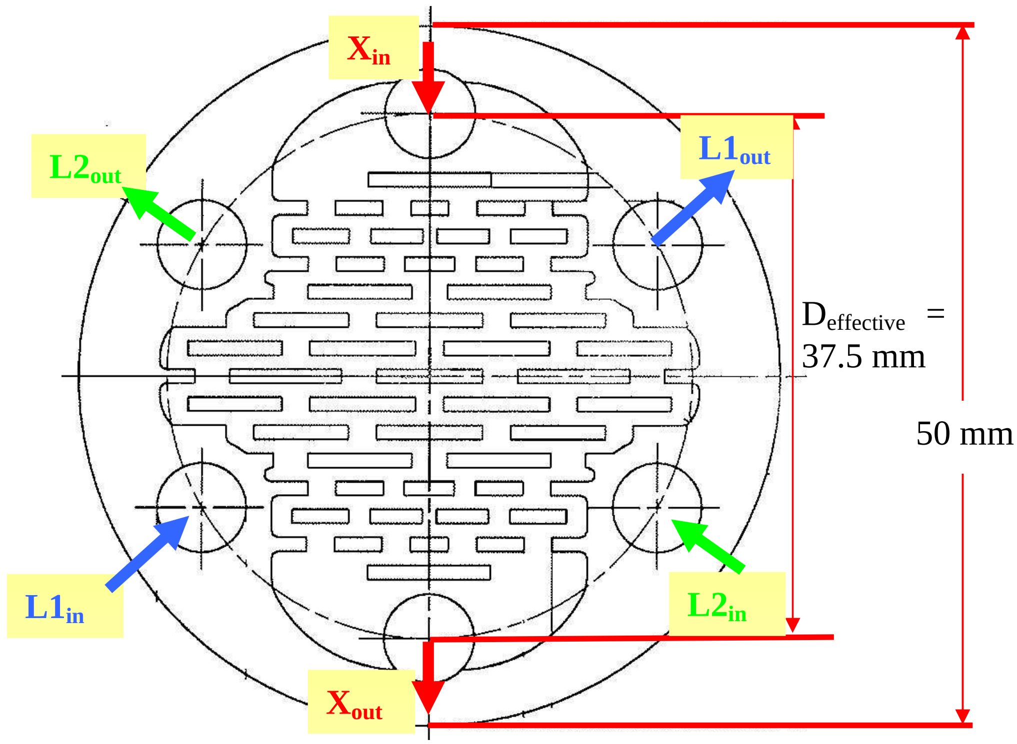

Figure 3-4: Drawing of one Bread Board Heat eXchanger plate

Figure 3-4 and *Figure 3-5* schematically show the various flows and flow directions. The total plate thickness t=1.5mm, the channel depth = 1.0mm and channel width = 1.0mm. The effective projected heat transfer area for one plate is $A_{pl,eff,,proj} = ¼ * \pi* (D_{eff})^2 = 1.1*10^{-3}$ m^2.

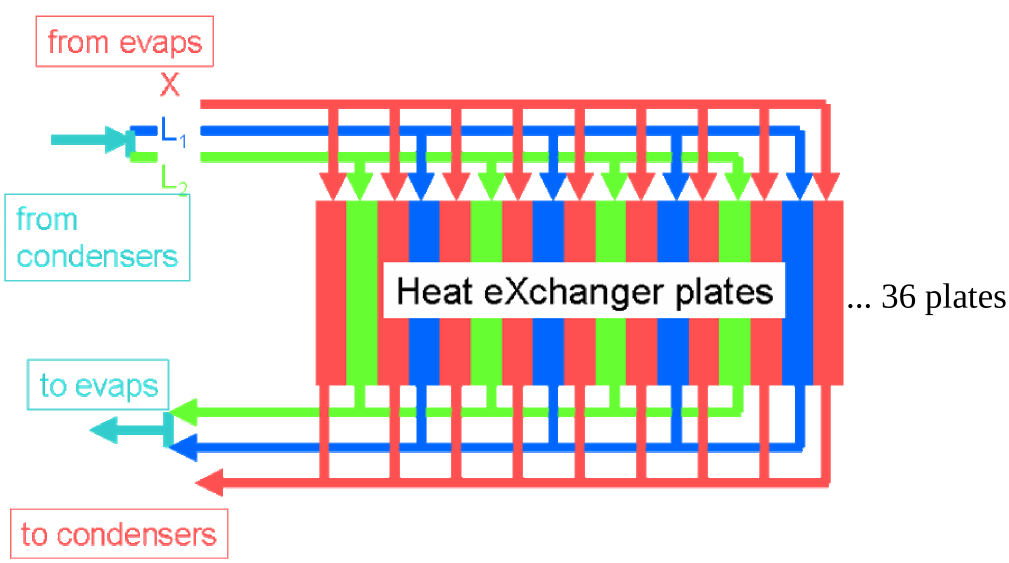

Figure 3-5: Flow through heat exchanger plates, schematically (X=two-phase, L=liquid)

4 Test approach and test set-up

4.1 Test approach

The overall heat transfer coefficient of a plate heat exchanger can be calculated using the following equations:

$OHTC=Q/(A_{HX,eff,pr}*\Delta T_{lm})$ where (1)

Q is transferred heat = $m*c_p*(T_{liq,out}-T_{liq,in})$ (2)

$A_{HX,eff,pr}$ is the total projected effective heat transfer area of the heat exchanger

$\Delta T_{lm} = (\Delta T_1-\Delta T_2)/\ln(\Delta T_1/\Delta T_2)$ (3)

$\Delta T_1 = T_{X,out}-T_{liq,in}$ (4)

$\Delta T_2 = T_{X,in}-T_{liq,out}$ (5)

$T_{X,in}$ and $T_{X,out}$ are the temperatures of the 2phase flow ; $T_{liq,in}$ and $T_{liq,out}$ are the temperatures of the liquid flow, where the subscripts 'in' and 'out' stand for the flow entering and leaving the HX respectively. During normal TTCS operation, CO_2 with a certain quality will enter the HX and will partly condensate to leave the HX with a lower quality. Through the other channels cold liquid will enter the HX to be heated inside and to leave it on a higher temperature closer to, but never higher than, the saturation temperature. *Figure 4-1* schematically shows how to handle fluid flows inside the HX from a thermal point of view; it can be simplified to just one liquid channel and one two-phase channel. Note that this 2-dimensional figure is not to be used to conclude anything on the flow type, such as counter flow, cross flow etc.

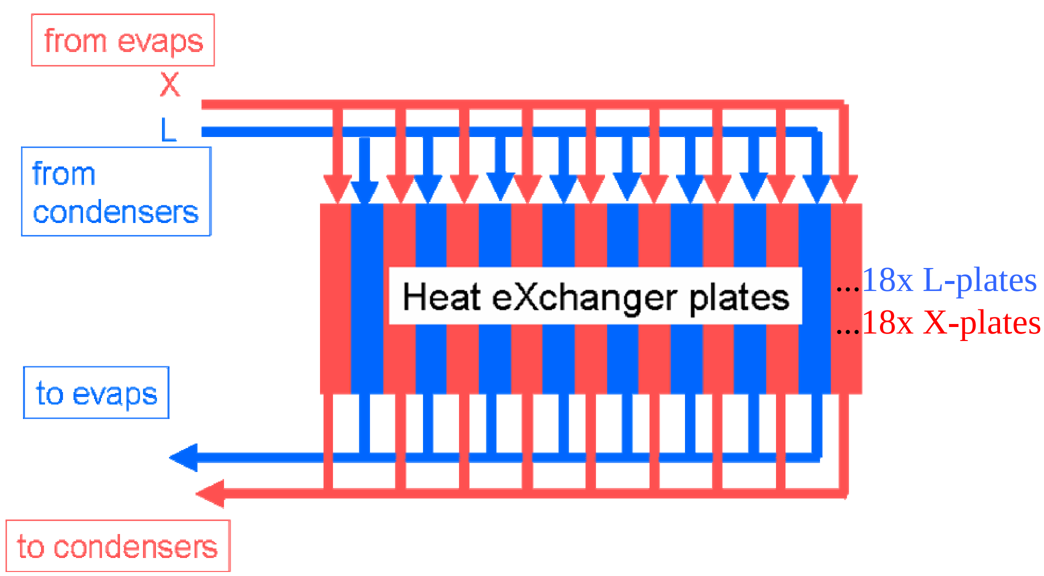

Figure 4-1: Equivalent flow through heat exchanger plates, schematically (X=two-phase, L=liquid)

As the nominal operation will be two-phase/liquid duty, during the tests it was attempted not to condensate all CO_2 vapour in the HX, by increasing the evaporator input power and hence the HX inlet quality where appropriate (usually at higher flow rates).

4.2 Set-up Description

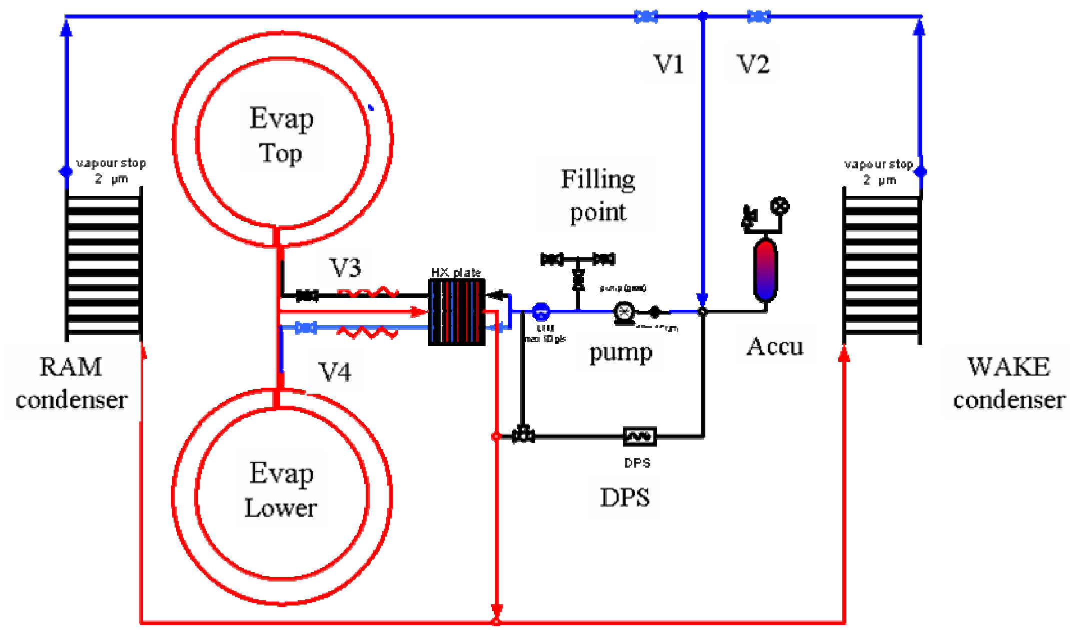

Figure 4-2: Test set-up, located in a climate chamber, nominally set to 0°C.

The test set-up, depicted in Figure 4-2, comprises two full size evaporators, two condensers, a one litre peltier controlled accumulator, a gear pump, two pre-heaters, insulated tubing, a differential and an absolute pressure sensor, lots of thermocouples and of course the plate heat exchanger which is the item under test. The set-up is located inside a temperature controlled chamber which is generally set a few degrees below the saturation temperature to minimize heat leak to the environment. However, despite the effort taken to insulate the tubing, heat losses to the environment are significant. Especially when the condenser temperatures are very low compared to the accu temperature, relative large heat leak occurs from the condenser return lines to the environment. When the chamber temperature is set to a much lower temperature than the accu temperature and hence the evaporator temperature, a large heat leak is measured from the evaporators to the environment. This heat leak can be measured by measuring the power required to keep a small dummy evaporator at saturation temperature. This feature however is to be controlled manually and was not used for all experiments that have been carried out.

Figure 4-3 show pictures of the main components of the test set-up inside the climate chamber.

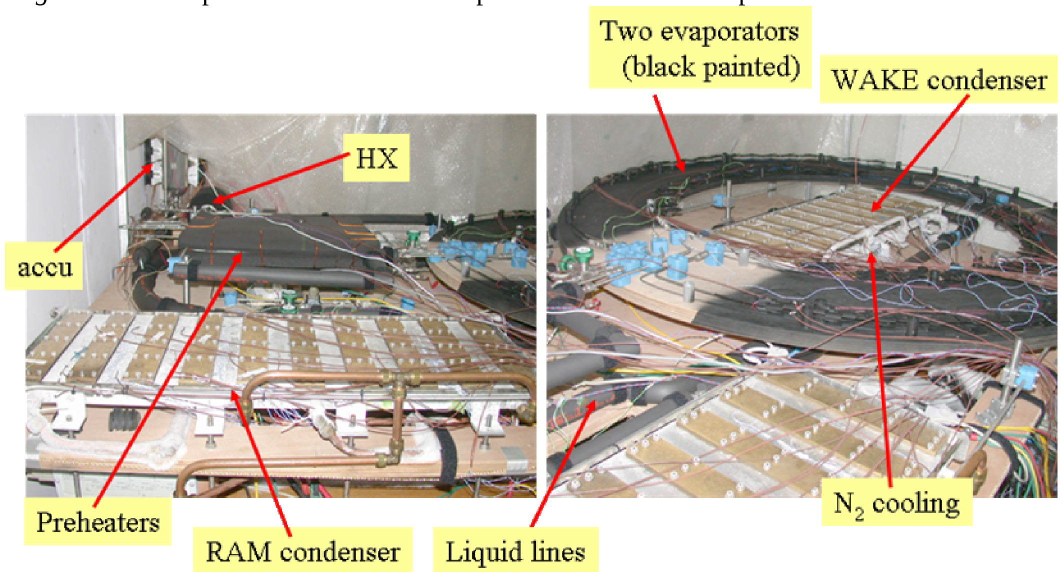

Figure 4-3: Overview pictures of the test set-up

5 Test Results

For various mass flow rates the inlet and outlet temperatures of the HX were measured while operating the HX in 2phase<->liquid duty. Test results can be found in *Table 5-1*. It became clear that, in order to keep the 2phase side outlet of the HX at a quality higher than 0%, a lot more than nominal power had to be put into the evaporators due to the efficiency of the HX. Even then, especially at larger flows, sub cooled liquid, in stead of 2phase flow, left the HX-2phase exit.

m_{tot} [g/s]	$L1_{in}/L2_{in}$ [℃]	$L1_{out}$ [℃]	$L2_{out}$ [℃]	$Top_{evap,out}$ [℃]	$Low_{evap,out}$ [℃]	$T\text{-}X_{out}$ [℃]	c_p [J/g]
2.0	-23.80	-1.54	-1.41	-1.08	-0.92	-0.92	2.28
3.5	-28.50	-2.04	-1.91	-1.01	-0.91	-1.24	2.21
5.0	-22.90	-3.80	-3.50	-1.40	-1.30	-6.90	2.28
6.5	-31.91	-5.64	-5.23	-0.91	-0.83	-10.35	2.21
8.0	-32.27	-5.93	-5.19	-0.65	-0.68	-9.90	2.21
10.0	-27.18	-8.53	-8.19	-0.09	0.03	-12.31	2.21

Table 5-1: Heat exchanger measurement data, 2phase<->liquid duty

Calculations were performed on these measurement data using equations 1 to 5 presented in section 4.1; the results are given in *Table 5-2*.

ΔT_1 [℃]	ΔT_2 [℃]	ΔT_{lm} [℃]	Q_{HX} [W]	OHTC (=U) [W/m^2.K]	$Q_{HXsubcl}$ [W]
0.48	22.88	5.78	102	457	0
1.02	27.26	7.98	205	668	2
2.30	16.00	7.06	219	807	63
4.57	21.56	10.95	380	902	136
4.90	22.37	11.50	472	1067	163
8.33	14.87	11.29	416	957	271

Table 5-2: Heat exchanger calculations based on measurements, 2phase<->liquid duty

Equivalent tests were carried out for liquid<->liquid duty. During nominal TTCS operation, liquid<->liquid duty will never occur, but test data will give an impression of the liquid-to-wall heat transfer to provide a better understanding of heat transfer phenomena of the HX . The results and calculations are given in *Table 5-3* and *Table 5-4.*

m_{tot} [g/s]	$L1/L2_{in}$ [℃]	$L1_{out}$ [℃]	$L2_{out}$ [℃]	Top_out [℃]	Low_out [℃]	$T\text{-}X_{out}$ [℃]	cp_hot [J/g]	cp_cold [J/g]
2.00	-18.20	-8.00	-8.00	-0.80	-0.50	-9.60	2.35	2.23
3.5	-21.3	-9.7	-9.6	-1.6	-1.7	-11.9	2.35	2.21
5	-23.1	-11.4	-11.3	-2.9	-3.3	-13.6	2.3	2.16
6.5	-23.6	-11.8	-11.7	-3.2	-3.4	-14	2.3	2.16
8	-23.9	-12.2	-12	-3.5	-3.7	-14.3	2.3	2.16
10	-23.2	-12.2	-12	-3.8	-3.9	-14.1	2.3	2.16

Table 5-3: Heat exchanger measurement data, liquid<->liquid duty

ΔT_1 [℃]	ΔT_2 [℃]	ΔT_{lm} [℃]	Qhot [W]	Qcold [W]	OHTC (=U) [W/m^2.K]
7.35	8.60	7.96	42	45	143
8.00	9.40	8.68	84	90	261
8.25	9.50	8.86	121	127	363
8.45	9.60	9.01	160	166	470
8.50	9.60	9.04	197	204	576
8.25	9.10	8.67	236	240	712

Table 5-4: Heat exchanger measurement data, 2phase<->liquid duty

Note that the hot and cold side power calculations, Q_{hot} and Q_{cold} representing the released and picked-up heat, are more or less identical giving confidence in the measurement method, thermo-couple locations and equipment used.

A graphical presentation of the calculated overall heat transfer coefficient is presented in *Figure 5-1*.

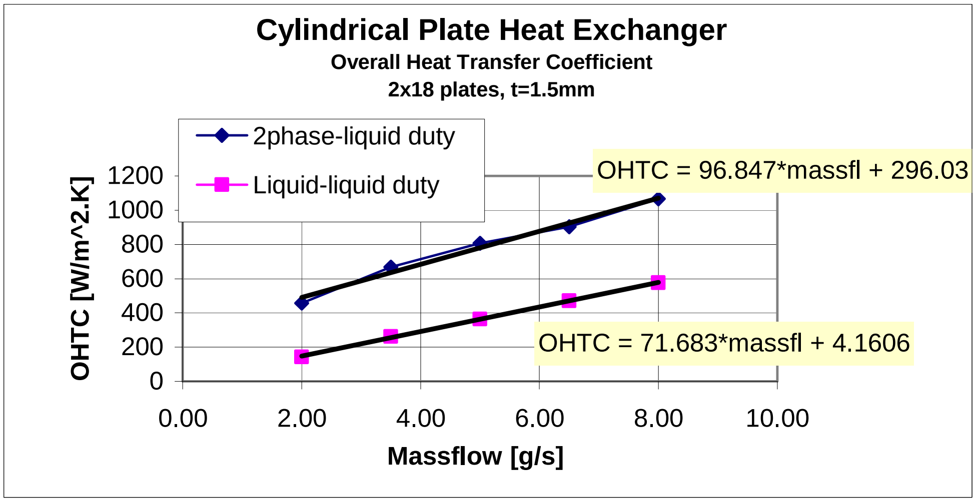

Figure 5-1:Heat transfer coefficient as function of massflow for 2phase<->liquid and liquid<->liquid duty

For 2phase<->liquid duty the following empirical equation is found for the OHTC as function of mass flow:

OHTC = 96.85*m + 296.0 [W/m^2.K] , m in [g/s] (6)

The conduction G = OHTC*$A_{HX,eff,proj}$ (7)

$A_{HX,eff,proj}$ = (n-1)* $A_{pl,eff,proj}$ (8)

For n=36 and $A_{pl,eff,proj}$ = 1.1*10^{-3} m^2 it is found that using eq. 7

G = OHTC*0.0385 and using eq. 6:

G = 3.73*m + 11.40 [W/K], m in [g/s] (9)

Note that for eq. 9 evaluation, ΔT_{lm} (eq. 3) is to be used.

Further on overall Heat eXchanger behaviour was tested during a typical orbital cycle, using realistic nominal settings for evaporator power and condenser heat sink temperatures. A graphical presentation of the measurement data is given in *Figure 5-2*. Theoretically the HX inlet temperature should be the average value of the condenser outlet temperatures, provided an even mass flow distribution through both condensers. However, because of heat in-leak from the environment combined with a low mass flow, the HX inlet temperature is higher. Nevertheless it is clear that the heat exchanger functions very well as the HX outlet temperature, which was measured upstream from the pre-heaters, is very close to saturation temperature. In the graph this temperature is even hard to distinguish from all evaporator temperatures.

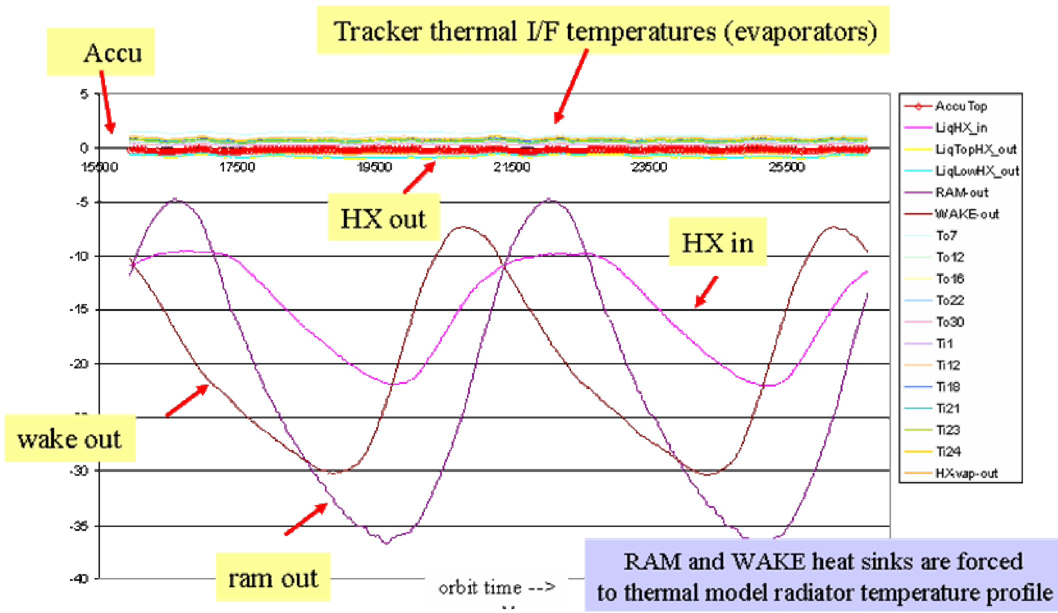

Figure 5-2: Measured test results of Heat eXchanger behaviour during a typical orbital cycle

6 Conclusions

- The heat exchanger Overall Heat Transfer Coefficient was successfully measured for 2phase<->liquid duty as well as for liquid<->liquid duty.
- The OHTC is mass flow dependent and increases with mass flow.
- At a nominal mass flow of 2 g/s the OHTC is 450 $W/m^2.K$ for 2phase<->liquid duty
- The HX was also successfully tested in a representative CO_2 laboratory test rig where typical orbital parameters were applied. The results showed satisfactory operation.

7 References

[1] HEAT EXCHANGERS, Kevin D. Rafferty, P.E., Gene Culver, Geo-Heat Center Klamath Falls, Oregon 97601

[2] Overzicht commercieel verkrijgbare warmtewisselaars: Technische en economische kentallen, S.F. Smeding, Juli 2001